Different types of wings evolved from the same ancestral tetrapod limb.

- Pterosaur wings consist of a membrane primarily supported by one greatly elongated finger.
- Bird wings consist of feathers supported by an elongated forearm and modified wrist and hand bones.
- Bat wings consist of a membrane supported by arm bones and four very elongated fingers.
Chapter 15: Big Ideas

Early Earth and the Origin of Life

Major Events in the History of Life

Mechanisms of Macroevolution

Phylogeny and the Tree of Life
EARLY EARTH AND
THE ORIGIN OF LIFE
The Earth formed about 4.6 billion years ago.

As the Earth cooled and the bombardment slowed about 3.9 billion years ago, the conditions on the planet were extremely different from those today.

- The first atmosphere was probably thick with
  - water vapor and
  - various compounds released by volcanic eruptions, including nitrogen and its oxides, carbon dioxide, methane, ammonia, hydrogen, and hydrogen sulfide.

- Lightning, volcanic activity, and ultraviolet radiation were much more intense than today.
The earliest evidence for life on Earth – comes from 3.5-billion-year-old fossils of stromatolites, built by ancient photosynthetic prokaryotes still alive today.

Because these 3.5-billion-year-old prokaryotes used photosynthesis, it suggests that life first evolved earlier, perhaps as much as 3.9 billion years ago.
The first life may have evolved through four stages.

1. The abiotic (nonliving) synthesis of small organic molecules, such as amino acids and nitrogenous bases.

2. The joining of these small molecules into polymers, such as proteins and nucleic acids.

3. The packaging of these molecules into “protocells,” droplets with membranes that maintained an internal chemistry different from that of their surroundings.

4. The origin of self-replicating molecules that eventually made inheritance possible.
In the 1920s, two scientists, the Russian A. I. Oparin and the British J. B. S. Haldane, independently proposed that organic molecules could have formed on the early Earth.

Our modern atmosphere is rich in $\text{O}_2$, which oxidizes and disrupts chemical bonds.

The early Earth likely had a reducing atmosphere.
In 1953, graduate student Stanley Miller, working under Harold Urey, tested the Oparin-Haldane hypothesis.

- Miller set up an airtight apparatus with gases circulating past an electrical discharge, to simulate conditions on the early Earth.
- He also set up a control with no electrical discharge.
Sparks simulating lightning

Water vapor

CH₄

“Atmosphere”

NH₃

H₂

Electrode

Condenser

Cold water

H₂O

“Sea”

Sample for chemical analysis

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After a week, Miller’s setup produced abundant amino acids and other organic molecules.

- Similar experiments used other atmospheres and other energy sources, with similar results.

- **Stage 1, abiotic synthesis of organic molecules**, was demonstrated to be possible by the Miller-Urey experiments.
Other hypotheses about the origins of life include

- deep sea environments near submerged volcanoes or hydrothermal vents or

- meteorites as sources of amino acids and other key organic molecules.
15.3 Stages in the origin of the first cells probably included the formation of polymers, protocells, and self-replicating RNA

- **Stage 2: The joining of monomers into polymers**
  - Hot sand, clay, or rock may have helped monomers combine to form polymers.
  - Waves may have splashed organic molecules onto fresh lava or other hot rocks and then rinsed polypeptides and other polymers back into the sea.
15.3 Stages in the origin of the first cells probably included the formation of polymers, protocells, and self-replicating RNA

- **Stage 3: Packaging of polymers into protocells**
  - Small membrane-bounded sacs or vesicles form when lipids are mixed with water.
  - These abiotically created vesicles are able to grow and divide (reproduce).
Stage 4: The origin of self-replicating molecules

- Today’s cells transfer genetic information from DNA to RNA to protein assembly. However, RNA molecules can assemble spontaneously from RNA monomers.

- RNA monomers in the presence of RNA molecules form new RNA molecules complementary to parts of the starting RNA.

- Some RNA molecules, called ribozymes, can carry out enzyme-like functions.
Figure 15.3B_s3

1 Collection of monomers

2 Formation of short RNA polymers: simple “genes”

3 Assembly of a complementary RNA chain, the first step in the replication of the original “gene”
MAJOR EVENTS IN THE HISTORY OF LIFE
Macroevolution is the broad pattern of changes in life on Earth.

The entire 4.6 billion years of Earth’s history can be broken into three eons of geologic time.

- The Archaean and Proterozoic eons lasted about 4 billion years.
- The Phanerozoic eon includes the last half billion years.
Figure 15.4

Archaean eon

Proterozoic eon

Phanerozoic eon

Animals

Colonization of land

Atmospheric oxygen

Single-celled eukaryotes

Multicellular eukaryotes

Prokaryotes

Origin of Earth

4.6 4 3 2 1 Present

Billions of years ago
Billions of years ago

Prokaryotes

Atmospheric oxygen

Origin of Earth

4.6

4

3

Billions of years ago

Archaean eon

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Figure 15.4_2

Proterozoic eon

Atmospheric oxygen

Single-celled eukaryotes

Multicellular eukaryotes

Phanerozoic eon

Colonization of land

Animals

Billions of years ago

Present

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Prokaryotes lived alone on Earth for 1.5 billion years, from 3.5 to 2 billion years ago.

- During this time, prokaryotes transformed the atmosphere.

- Prokaryotic photosynthesis produced oxygen that enriched the water and atmosphere of Earth.

- Anaerobic and aerobic cellular respiration allowed prokaryotes to flourish.
The oldest fossils of eukaryotes are about 2.1 billion years old.

The common ancestor of all multicellular eukaryotes lived about 1.5 billion years ago.

The oldest fossils of multicellular eukaryotes are about 1.2 billion years old.

The first multicellular plants and fungi began to colonize land about 500 million years ago.
Humans diverged from other primates about 6 to 7 million years ago.

Our species, *Homo sapiens*, originated about 195,000 years ago.

If the Earth’s history were compressed into an hour, humans appeared less than 0.2 seconds ago!
Radiometric dating measures the decay of radioactive isotopes.

The rate of decay is expressed as a half-life, the time required for 50% of an isotope in a sample to decay.

There are many different isotopes that can be used to date fossils. These isotopes have different half-lives, ranging from thousands to hundreds of millions of years.
15.5 The actual ages of rocks and fossils mark geologic time

- The age of a fossil can also be inferred from the ages of rock layers above and below the strata in which a fossil is found.
The geologic record is based on the sequence and age of fossils in the rock strata.

The most recent Phanerozoic eon
- includes the past 542 million years and
- is divided into three eras
  - Paleozoic,
  - Mesozoic, and
  - Cenozoic.

The boundaries between eras are marked by mass extinctions.
### Table 15.6: The Geologic Record

<table>
<thead>
<tr>
<th>Era</th>
<th>Period</th>
<th>Epoch</th>
<th>Age (millions of years ago)</th>
<th>Important Events in the History of Life</th>
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<td>Permian</td>
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<td>Silurian</td>
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<td>Ordovician</td>
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<td>Ediacaran</td>
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<td>Approx. 4,600</td>
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<table>
<thead>
<tr>
<th>Era</th>
<th>Period</th>
<th>Epoch</th>
<th>Age (millions of years ago)</th>
<th>Important Events in the History of Life</th>
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<tr>
<td>Cenozoic</td>
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<td>Holocene</td>
<td>Historical time</td>
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<td>Phanerozoic</td>
<td>Quaternary</td>
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<td>Pleistocene</td>
<td>Ice ages; origin of genus <em>Homo</em></td>
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<td></td>
<td>Pliocene</td>
<td>Appearance of bipedal human ancestors</td>
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<td></td>
<td></td>
<td>Miocene</td>
<td>Continued radiation of mammals and angiosperms; earliest direct human ancestors</td>
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<td>Oligocene</td>
<td>Origins of many primate groups</td>
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<td></td>
<td></td>
<td>Eocene</td>
<td>Angiosperm dominance increases; continued radiation of most present-day mammalian orders</td>
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<tr>
<td></td>
<td></td>
<td>Paleocene</td>
<td>Major radiation of mammals, birds, and pollinating insects</td>
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<tr>
<td>Proterozoic</td>
<td>Mesozoic</td>
<td></td>
<td>Cretaceous</td>
<td>Flowering plants (angiosperms) appear and diversify; many groups of organisms, including most dinosaurs, become extinct at end of period</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jurassic</td>
<td>Gymnosperms continue as dominant plants; dinosaurs abundant and diverse</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Triassic</td>
<td>Cone-bearing plants (gymnosperms) dominate landscape; dinosaurs evolve and radiate; origin of mammals</td>
<td></td>
</tr>
<tr>
<td>Order</td>
<td>Relative Duration of Eons</td>
<td>Epoch Age (Millions of Years Ago)</td>
<td>Important Events in the History of Life</td>
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<tr>
<td>-------------------</td>
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<tr>
<td>Paleozoic</td>
<td></td>
<td></td>
<td>Radiation of reptiles; origin of most present-day groups of insects; extinction of many marine and terrestrial organisms at end of period</td>
<td></td>
</tr>
<tr>
<td>Permian</td>
<td></td>
<td>251</td>
<td>Radiation of reptiles; origin of most present-day groups of insects; extinction of many marine and terrestrial organisms at end of period</td>
<td></td>
</tr>
<tr>
<td>Carboniferous</td>
<td></td>
<td>359</td>
<td>Extensive forests of vascular plants form; first seed plants appear; origin of reptiles; amphibians dominant</td>
<td></td>
</tr>
<tr>
<td>Devonian</td>
<td></td>
<td>416</td>
<td>Diversification of bony fishes; first tetrapods and insects appear</td>
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</tr>
<tr>
<td>Silurian</td>
<td></td>
<td>444</td>
<td>Diversification of early vascular plants</td>
<td></td>
</tr>
<tr>
<td>Ordovician</td>
<td></td>
<td>488</td>
<td>Marine algae abundant; colonization of land by diverse fungi, plants, and animals</td>
<td></td>
</tr>
<tr>
<td>Cambrian</td>
<td></td>
<td>542</td>
<td>Sudden increase in diversity of many animal phyla (Cambrian explosion)</td>
<td></td>
</tr>
<tr>
<td>Ediacaran</td>
<td></td>
<td>635</td>
<td>Diverse algae and soft-bodied invertebrate animals appear</td>
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<tr>
<td></td>
<td></td>
<td>2,100</td>
<td>Oldest fossils of eukaryotic cells appear</td>
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<tr>
<td></td>
<td></td>
<td>2,500</td>
<td>Oldest fossils of eukaryotic cells appear</td>
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<td></td>
<td></td>
<td>2,700</td>
<td>Concentration of atmospheric oxygen begins to increase</td>
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<td></td>
<td>3,500</td>
<td>Oldest fossils of cells (prokaryotes) appear</td>
<td></td>
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<td></td>
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<td>3,800</td>
<td>Oldest known rocks on Earth's surface</td>
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<td></td>
<td></td>
<td>Approx. 4,600</td>
<td>Origin of Earth</td>
<td></td>
</tr>
</tbody>
</table>
MECHANISMS OF MACROEVOLUTION
According to the theory of **plate tectonics**, the Earth’s crust is divided into giant, irregularly shaped plates that essentially float on the underlying mantle.

In a process called continental drift, movements in the mantle cause the plates to move.

Since the origin of multicellular life roughly 1.5 billion years ago, there have been three occasions in which the landmasses of Earth came together to form a supercontinent.
Figure 15.7B

Zones of violent tectonic activity

Direction of movement

North American Plate

Caribbean Plate

Juan de Fuca Plate

Cocos Plate

Pacific Plate

Nazca Plate

South American Plate

Arabian Plate

Indian Plate

African Plate

Australian Plate

Eurasian Plate

Philippine Plate

Scotia Plate

Antarctic Plate

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About 250 million years ago

- plate movements brought all the landmasses together and
- the supercontinent of Pangaea was formed.

During the Mesozoic era,

- Pangaea started to break apart,
- the physical environment and climate changed dramatically,
- Australia became isolated, and
- biological diversity was reshaped.
Figure 15.7C

Millions of years ago

Paleozoic

1. 251

2. 135

3. 65.5

4. Present

Cenozoic

Mesozoic

Pangaea

Laurasia

Gondwana

North America

Eurasia

Africa

South America

India

Madagascar

Antarctica

Australia
Figure 15.7C_1

Present

Cenozoic

65.5

Millions of years ago

Mesozoic

135

Gondwana

Laurasia

North America

Eurasia

Africa

South America

India

Madagascar

Australia

Antarctica

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Figure 15.7C_2

Millions of years ago

1. Paleozoic
2. Mesozoic

251

2

Laurasia

Gondwana

Pangaea

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Continental drift explains the distribution of lungfishes.

- Fossils of lungfishes are found on every continent except Antarctica.
- Today, living lungfishes are found in
  - South America,
  - Africa, and
  - Australia.
- This evidence suggests that lungfishes evolved when Pangaea was still intact.
Figure 15.7D

North America
South America
Africa
Europe
Asia
Australia

Living lungfishes
Fossilized lungfishes
Figure 15.7D_1

North America

South America

Africa

Europe

Asia

Australia

Living lungfishes

Fossilized lungfishes
15.8 CONNECTION: Plate tectonics may imperil human life

- Volcanoes and earthquakes result from the movements of crustal plates.
  - The boundaries of plates are hotspots of volcanic and earthquake activity.
  - An undersea earthquake caused the 2004 tsunami, when a fault in the Indian Ocean ruptured.
Figure 15.8

San Andreas Fault
Pacific Plate
North American Plate
San Francisco
Los Angeles
California
Extinction is inevitable in a changing world.

The fossil record shows that the vast majority of species that have ever lived are now extinct.

Over the last 500 million years,

– five mass extinctions have occurred, and

– in each event, more than 50% of the Earth’s species went extinct.
During mass extinctions, large numbers of species are lost

The Permian mass extinction

- occurred about 251 million years ago,
- defines the boundary between the Paleozoic and Mesozoic eras,
- claimed 96% of marine animal species,
- took a tremendous toll on terrestrial life, and
- was likely caused by enormous volcanic eruptions.
15.9 During mass extinctions, large numbers of species are lost

- The Cretaceous mass extinction
  - caused the extinction of all the dinosaurs except birds and
  - was likely caused by a large asteroid that struck the Earth, blocking light and disrupting the global climate.
Figure 15.9

Asteroid

North America

Yucatán Peninsula

Chicxulub crater
15.9 During mass extinctions, large numbers of species are lost

- Mass extinctions affect biological diversity profoundly.

- It took 100 million years for the number of marine families to recover after Permian mass extinction.

- Is a sixth extinction under way?
  - The current extinction rate is 100–1,000 times the normal background rate.
  - It may take life on Earth millions of years to recover.
Adaptive radiations are periods of evolutionary change that occur when many new species evolve from a common ancestor that colonizes a new, unexploited area and often follow extinction events.

Radiations may result from the evolution of new adaptations such as wings in pterosaurs, birds, bats, and insects and adaptations for life on land in plants, insects, and tetrapods.
Figure 15.10

Extinction of dinosaurs

- Ancestral mammal
- Reptilian ancestor

Monotremes (5 species)
Marsupials (324 species)
Eutherians (placental mammals; 5,010 species)

Time (millions of years ago)
15.11 Genes that control development play a major role in evolution

- The fossil record can tell us
  - *what* the great events in the history of life have been and
  - *when* they occurred.

- Continental drift, mass extinctions, and adaptive radiation provide a big-picture view of *how* those changes came about.

- We are now increasingly able to understand the basic biological mechanisms that underlie the changes seen in the fossil record.
The field of **evo-devo**

- addresses the interface of evolutionary biology and developmental biology and
- examines how slight genetic changes can produce major morphological differences.

Genes that program development control the

- rate,
- timing, and
- spatial pattern of change in an organism’s form as it develops.
Animation: Allometric Growth
Right click on animation / Click play
Many dramatic evolutionary transformations are the result of a change in the rate or timing of developmental events.

**Paedomorphosis**
- is the retention in the adult of body structures that were juvenile features in an ancestral species and
- occurs in the axolotl salamander in which sexually mature adults retain gills and other larval features.
Figure 15.11A

Gills
Slight changes in the relative growth of different body parts can change an adult form substantially.

- Skulls of humans and chimpanzees are
  - more similar as fetuses but
  - quite different as adults due to different rates of growth.
15.11 Genes that control development play a major role in evolution

- **Homeotic genes**
  - are called master control genes and
  - determine basic features, such as where pairs of wings or legs develop on a fruit fly.

- Profound alterations in body form can result from
  - changes in homeotic genes or
  - how or where homeotic genes are expressed.
Duplication of developmental genes can also be important in the formation of new morphological features.

- A fruit fly has a single cluster of homeotic genes.
- A mouse has four clusters of homeotic genes.
- Two duplications of these gene clusters occurred in the evolution of vertebrates from invertebrates.
In the threespine stickleback fish, those fish that live

- in the ocean have bony plates and a large set of pelvic spines but
- in lakes have reduced or absent bony plates and pelvic spines, resulting from a change in the expression of a developmental gene in the pelvic region.
Figure 15.11C

Missing pelvic spine
In most cases, complex structures evolve by increments from simpler versions with the same basic functions.

In the evolution of an eye or any other complex structure, behavior, or biochemical pathway, each step must

- bring a selective advantage to the organism possessing it and
- increase the organism’s fitness.
Mollusc eyes evolved from an ancestral patch of photoreceptor cells through a series of incremental modifications that were adaptive at each stage.

A range of complexity can be seen in the eyes of living molluscs.

Cephalopod eyes are as complex as vertebrate eyes, but arose separately.
Figure 15.12

Patch of pigmented cells
Pigmented cells (photoreceptors)

Eyecup

Simple pinhole eye
Fluid-filled cavity

Eye with primitive lens
Transparent protective tissue (cornea)

Complex camera lens-type eye

Limpet
Abalone
Nautilus
Marine snail
Squid

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Figure 15.12_1

Patch of pigmented cells
Pigmented cells (photoreceptors)
Nerve fibers

Limpet

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Simple pinhole eye

Fluid-filled cavity

Layer of pigmented cells (retina)

Optic nerve

Nautilus
Figure 15.12_4

Eye with primitive lens
Transparent protective tissue (cornea)

Layer of pigmented cells (retina)

Optic nerve

Marine snail
Figure 15.12_5

Complex camera lens-type eye

Cornea

Lens

Retina

Optic nerve

Squid

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In other cases, evolutionary novelties result from the gradual adaptation of existing structures to new functions.

Such structures that evolve in one context but become co-opted for another function are often called *exaptations*.

Examples of exaptations include

- feathers that may have first functioned for insulation and later were co-opted for flight and
- flippers of penguins that first functioned for flight and were co-opted for underwater swimming.
The fossil record seems to reveal trends in the evolution of many species, but identifying trends can be problematic.

The evolution of horses reveals a potential misunderstanding.

- If we select only certain species in this family tree, it appears that there was a general trend toward the reduction in the number of toes, larger size, and teeth modified for grazing.

- However, if we consider all of the known members of this family tree, this apparent trend vanishes.
Figure 15.13

Millions of years ago, the evolution of horses included a variety of species adapted for grazing and browsing. Over time, the teeth of these species evolved, with grazers having teeth adapted for grazing and browsers having teeth adapted for browsing.

- **Grazers:** teeth adapted for grazing
- **Browsers:** teeth adapted for browsing

Species include:
- Anchitherium
- Equus
- Pliohippus
- Merychippus
- Parahippus
- Archaeohippus
- Sinohippus
- Megahippus
- Orohippus
- Propalaeotherium
- Pachynolophus
- Palaeotherium
- Mesotherium
- Mesotherium
- Epihippus
- Callippus
- Neohipparion
- Nannippus
- Callippus
- Hipparion
- Hyracotherium

Present-day species include:
- Hipparion
- Neohipparion
- Nannippus
- Callippus
- Mesohippus
- Epihippus
- Callippus
- Palaeotherium
- Propalaeotherium
- Pachynolophus
- Palaeotherium
- Mesotherium
- Epihippus
- Callippus
- Hipparion
- Hyracotherium
Figure 15.13_1

Millions of years ago

Present

Equus

Anchitherium

Merychippus

Callippus

Sinohippus

Megahippus

Hypohippus

Archaeohippus

Parahippus

Grazers

Browsers

Equus

Pliohippus

Hipparion

Neohipparion

Nannippus

Hippidion and close relatives

Megahippus

Sinohippus

Anchitherium

Parahippus

Merychippus
Figure 15.13_2

Millions of years ago

Propalaeotherium
Pachynolophus
Palaeotherium

Miohippus

Mesohippus

Orohippus

Hyracotherium

Grazers: teeth adapted for grazing

Browsers: teeth adapted for browsing

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Branching evolution can lead to genuine trends.

The species selection model of long-term trends compares species to individuals.

- Speciation is their birth,
- extinction their death, and
- new species that diversify from them are their offspring.
- Unequal survival of species and unequal generation of new species play a role in macroevolution similar to the role of unequal reproduction in microevolution.
Evolutionary trends can also result directly from natural selection. For example,

- when horse ancestors invaded the grasslands that spread during the mid-Cenozoic,
- there was strong selection for grazers that could escape predators by running fast.

Whatever its cause, it is important to recognize that an evolutionary trend does not imply that evolution is goal directed.

Evolution is the result of interactions between organisms and the current environment.
PHYLOGENY AND THE TREE OF LIFE
Phylogeny is the evolutionary history of a species or group of species.

Phylogeny can be inferred from

- the fossil record,
- morphological homologies, and
- molecular homologies.
Homologies are similarities due to shared ancestry, evolving from the same structure in a common ancestor.

Generally, organisms that share similar morphologies are closely related.

- However, some similarities are due to similar adaptations favored by a common environment, a process called **convergent evolution**.
- A similarity due to convergent evolution is called **analogy**.
15.15 Systematics connects classification with evolutionary history

- **Systematics** is a discipline of biology that focuses on
  - classifying organisms and
  - determining their evolutionary relationships.

- Carolus Linnaeus introduced **taxonomy**, a system of naming and classifying species.
Biologists assign each species a two-part scientific name, or **binomial**, consisting of

- a **genus** and
- a unique part for each species within the genus.

Genera are grouped into progressively larger categories.

Each taxonomic unit is a **taxon**.
Animation: Classification Schemes
Right click on animation / Click play
Species: *Felis catus*

Genus: *Felis*

Family: *Felidae*

Order: *Carnivora*

Class: *Mammalia*

Phylum: *Chordata*

Kingdom: *Animalia*

Domain: *Eukarya*

Archaea

Bacteria
Biologists traditionally use **phylogenetic trees** to depict hypotheses about the evolutionary history of species.

- The branching diagrams reflect the hierarchical classification of groups nested within more inclusive groups.

- Phylogenetic trees indicate the probable evolutionary relationships among groups and patterns of descent.
Order | Family | Genus | Species
--- | --- | --- | ---
Felis catus (domestic cat) | Felidae | Felis |
Mustela frenata (long-tailed weasel) | Mustelidae | Mustela |
Lutra lutra (European otter) | Lutra |
Canis latrans (coyote) | Canidae | Canis |
Canis lupus (wolf) | Canidae | Canis |
Carnivora | | |
15.16 Shared characters are used to construct phylogenetic trees

- **Cladistics**
  - is the most widely used method in systematics and
  - groups organisms into clades.

- Each clade is a **monophyletic** group of species that
  - includes an ancestral species and
  - all of its descendants.
Cladistics is based on the Darwinian concept that organisms share characteristics with their ancestors and differ from them. Thus, there are two main types of characters.

1. **Shared ancestral characters** group organisms into clades.

2. **Shared derived characters** distinguish clades and form the branching points in the tree of life.
An important step in cladistics is the comparison of the

- **ingroup** (the taxa whose phylogeny is being investigated) and

- **outgroup** (a taxon that diverged before the lineage leading to the members of the ingroup),

- to identify the derived characters that define the branch points in the phylogeny of the ingroup.
As an example, consider
- a frog representing the outgroup and
- four other tetrapods representing the ingroup.

The presence or absence of traits is indicated as
- 1 if the trait is present or
- 0 if the trait is absent.
**Character Table**

<table>
<thead>
<tr>
<th>Characters</th>
<th>Frog</th>
<th>Iguana</th>
<th>Duck-billed platypus</th>
<th>Kangaroo</th>
<th>Beaver</th>
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<td>Long gestation</td>
<td>0</td>
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<td>0</td>
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</tbody>
</table>

**Phylogenetic Tree**

- **Frog**
- **Iguana**
- **Duck-billed platypus**
- **Kangaroo**
- **Beaver**
### Character Table

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<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Graphical representation of the character table.
Figure 15.16A_2

Amnion

Long gestation

Phylogenetic Tree
In our example, the phylogenetic tree is constructed from a series of branch points, represented by the emergence of a lineage with a new set of derived traits.

When constructing a phylogenetic tree, scientists use **parsimony**, looking for the simplest explanation for observed phenomena.

- Systematists use many kinds of evidence. However, even the best tree represents only the most likely hypothesis.
The phylogenetic tree of reptiles shows that crocodilians are the closest *living* relatives of birds.

- They share numerous features, including
  - four-chambered hearts,
  - “singing” to defend territories, and
  - parental care of eggs within nests.
- These traits were likely present in the common ancestor of birds, crocodiles, and dinosaurs.
Common ancestor of crocodilians, dinosaurs, and birds

- Lizards and snakes
- Crocodilians
- Pterosaurs*
- Ornithischian dinosaurs*
- Saurischian dinosaurs*
- Birds
15.17 An organism’s evolutionary history is documented in its genome

- **Molecular systematics** uses DNA and other molecules to infer relatedness.
  - Scientists have sequenced more than 110 billion bases of DNA from thousands of species.
  - This enormous database has fueled a boom in the study of phylogeny and clarified many evolutionary relationships.
Figure 15.17

Millions of years ago

35 30 25 20 15 10

Oligocene
Miocene
Pliocene
Pleistocene

Red panda
Weasel
Raccoon
Giant panda
Spectacled bear
Sloth bear
Sun bear
American black bear
Asian black bear
Polar bear
Brown bear

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Millions of years ago

35 30 25 20 15 10

Oligocene Miocene Pliocene Pleistocene

Red panda
Weasel
Raccoon
Giant panda
Spectacled bear
Sloth bear
Figure 15.17.1

Sun bear
American black bear
Asian black bear
Polar bear
Brown bear

35 30 25 20 15 10

Oligocene
Miocene
Pliocene
Pleistocene

Millions of years ago

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The more recently two species have branched from a common ancestor, the more similar their DNA sequences should be.

The longer two species have been on separate evolutionary paths, the more their DNA should have diverged.
Different genes evolve at different rates.

- DNA coding for ribosomal RNA (rRNA)
  - changes slowly and
  - is useful for investigating relationships between taxa that diverged hundreds of millions of years ago.
- In contrast, DNA in mitochondria (mtDNA)
  - evolves rapidly and
  - is more useful to investigate more recent evolutionary events.
The remarkable commonality of molecular biology demonstrates that all living organisms share many biochemical and developmental pathways and provides overwhelming support of evolution.

- The genomes of humans and chimpanzees are amazingly similar.
- About 99% of the genes of humans and mice are detectably homologous.
- About 50% of human genes are homologous with those of yeast.
Molecular clocks

- rely on genes that have a reliable average rate of change,
- can be calibrated in real time by graphing the number of nucleotide differences against the dates of evolutionary branch points known from the fossil record,
- are used to estimate dates of divergences without a good fossil record, and
- have been used to date the origin of HIV infection in humans.
Figure 15.18

Differences between HIV sequences

Year

HIV

Range

Line of best fit to data points

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Molecular systematics and cladistics are remodeling some trees.

Biologists currently recognize a three-domain system consisting of

- two domains of prokaryotes: Bacteria and Archaea, and
- one domain of eukaryotes called Eukarya including
  - fungi,
  - plants, and
  - animals.
Molecular and cellular evidence indicates that

- Bacteria and Archaea diverged very early in the evolutionary history of life and
- Archaea are more closely related to eukaryotes than to bacteria.
Comparisons of complete genomes from all three domains show that

- there have been substantial interchanges of genes between organisms in different domains and
- these took place through **horizontal gene transfer**, a process in which genes are transferred from one genome to another through mechanisms such as plasmid exchange and viral infection.

Some biologists suggest that the early history of life may be best represented by a ring, from which the three domains emerge.
1. Most recent common ancestor of all living things
2. Gene transfer between mitochondrial ancestor and ancestor of eukaryotes
3. Gene transfer between chloroplast ancestor and ancestor of green plants

Billions of years ago

- Bacteria
- Eukarya
- Archaea
You should now be able to

1. Describe the conditions on the surface of the early Earth. Describe the evidence that life on Earth existed at least 3.5 billion years ago.

2. Describe the four stages that might have produced the first cells on Earth.

3. Describe the experiments of Stanley Miller and others in understanding how life might have first evolved on Earth.

4. Describe the significance of protocells and ribozymes in the origin of the first cells.

5. Describe the key events in the history of life on Earth.
6. Explain how radiometric dating and the relative position of a fossil within rock strata are used to determine the age of rocks.

7. Briefly describe the history of life on Earth. Describe the key events that serve to divide the eras.

8. Describe how Earth’s continents have changed over the past 250 million years and the consequences of these changes for life on Earth.

9. Explain how volcanoes and earthquakes result from plate tectonics.

10. Describe the causes, frequency, and consequences of mass extinctions over the last 500 million years.
11. Explain how and why adaptive radiations occur.

12. Explain how genes that program development function in the evolution of life. Define and describe examples of paedomorphosis.

13. Define exaptation and describe two examples in birds.

14. Explain why evolutionary trends do not reflect “directions” or “goals.”

15. Distinguish between homologous and analogous structures and provide examples of each. Describe the process of convergent evolution.
16. Describe the goals of systematics. List the progressively broader categories of classification used in systematics in order, from most specific to most general.

17. Define the terms clade, monophyletic groups, shared derived characters, shared ancestral characters, ingroup, outgroup, phylogenetic trees, and parsimony.

18. Explain how molecular biology is used as a tool in systematics.

19. Explain how molecular clocks are used to track evolutionary time.

20. Explain why a diagram of the tree of life is difficult to construct.
First prokaryotes (single-celled)

First eukaryotes (single-celled)

First multicellular eukaryotes

Colonization of land by fungi, plants, and animals

Billions of years ago

4 3.5 3 2.5 2 1.5 1 .5 Present
Systematics generates hypotheses for constructing evolutionary history called based on seen in (e) using analysis identifies shared ancestral characters using determine sequence of branch points using must distinguish from nucleotide sequences (c) (d) (f) (g) (b) (a)
<table>
<thead>
<tr>
<th>Trait</th>
<th>Velociraptor</th>
<th>Coelophysis</th>
<th>Archaeopteryx</th>
<th>Allosaurus</th>
</tr>
</thead>
<tbody>
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<td>Hollow bones</td>
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<td>1</td>
<td>1</td>
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<tr>
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